DESIGNING HIGH PERFORMANCE CONCRETE FOR SERVICE LIFE AND SUSTAINABILITY OF STRUCTURES

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ABSTRACT. Availability of new generation cementitious materials and additives has enabled concrete manufacturing industry to proportion high performance concrete (HPC) mixtures catering to customised needs of specific construction projects. This paper compiles various emerging concrete varieties which have been designed for the enhanced performance of structures in terms of durability, service life and sustainability. The concrete types that have been evaluated in this study are Self compacting concrete, enhanced durability concrete, mass concrete, and lightweight insulating concrete. The usage of admixtures, microfine pozzolans, lightweight aggregates, viscosity modifying agents and crystalline polymers has been incorporated. The process of mixture proportioning has been demonstrated with laboratory and field examples. The process includes assessment of service life and sustainability parameters based on project requirements, characterisation of available speciality additives and testing of special properties offered by respective additions. Compressive strength, workability, flowability, water and chloride permeability, and thermal conductivity have been reported for specific combinations. The paper also summarises an indicative impact of the results on the service life of the structures and sustainability benefits. The conclusions of the paper demonstrate that concrete can be modified into a superior material in terms these goals by proportioning of mixtures involving advanced materials.

Keywords: Durability, Sustainability, HPC, Service life, pozzolans, RCPT

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INTRODUCTION

High Performance Concrete (HPC) is defined as a concrete engineered to meet specific needs of a project including: mechanical, durability, or constructability properties exceeding those of normal concrete1. With the advent of high performance structures like high rise buildings, metro rail transport, monorail, bullet train, and buildings with high durability and aesthetic requirements, there is a paradigm shift in what concrete is expected to deliver. The design parameters which such concrete targets to achieve are often driven by multiple specifications derived from various international codes like ACI, ASTM, BS-EN, DIN etc. Typically, 21st Century concrete specifications are driven by later age compressive strengths, rapid chloride ion penetration test (RCPT), water permeability and initial surface absorption test (ISAT) and flowability. The focus of mix proportioning goes beyond the traditional approach and involves characterizing newer cementitious materials and additives. The approach used for HPC mixture proportioning is being demonstrated with field data from four such structures.

SELF COMPACTING CONCRETE (SCC) FOR MONORAIL PROJECT

Project Requirements

The project needed to cast 500 piers 10 metre high with 50 mm rebar spacing and 600mm wide beam girder stitches of Monorail with 20mm rebar spacing. The compressive strength required for these elements was M45 for piers and M60 for beam girder joints. Apart from durability parameters and early strength requirements, the structural elements were also expected to demonstrate good aesthetic appearance by way of superior surface finish. In order to achieve this extraordinary performance coupled with time bound completion schedule of the project, SCC was selected as preferred concrete type.

Design Stipulations

Grade of Concrete :	M45 and M60	Maximum water-binder ratio :	0.45
Slump Flow :	SF3 (760-850mm)	Maximum RCPT value :	1000 coulombs

Material Selection and Design Approach

Mix proportioning of SCC focuses more on water to powder ratio by volume. Factors such as paste content, water content and fine aggregate to coarse aggregate proportioning have large influence on SCC properties. Use of flyash, Polycarboxyllate (PCE) based superplasticisers and viscosity modifying admixtures was adopted to complement achieving selected SCC characteristics.

According to European guidelines (Figure 1) SCC is broadly classified in SF1, SF2 and SF3 based on application area and their subsequent performance requirements. Mumbai Monorail structures were classified under SF3 category which is highly demanding category within SCC classes. VS1/VF1 class was selected because of good filling ability, self-levelling and surface finish capabilities. SR2 class was preferred because flow distance was more than 5 metres and confinement gap greater than 80 mm in order to take care of segregation during flow. Production of consistent quality of SF3 class SCC with locally available raw materials like manufactured sand was major mix proportioning challenge. A smaller maximum size of aggregates of 12.5 mm was used considering vertical application in a very congested structure. Table 1 demonstrates a summary of target SCC classes.

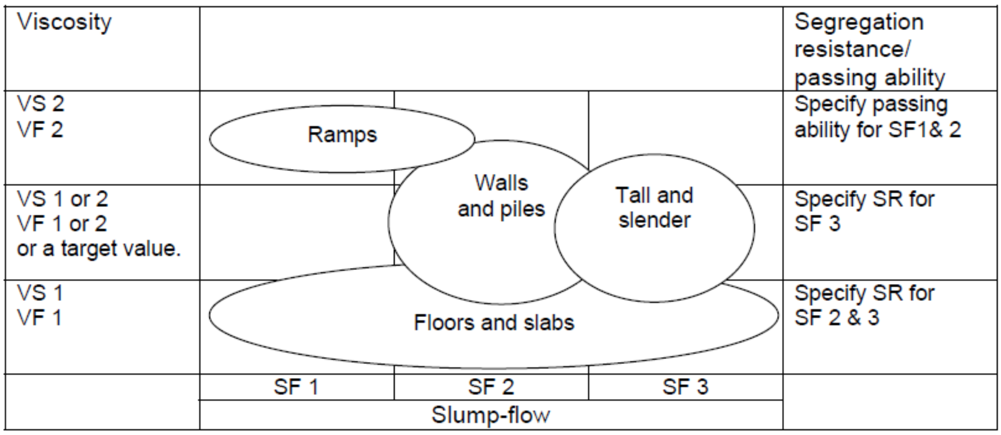

Figure1 Properties of SCC for various types of application (Source – European Guidelines for Self-compacting Concrete).

Table 1 Summary of target SCC classes for monorail piers and girder joints

CHARACTERISTICS	TEST METHOD	CLASS	MEASURED VALUE
Flowability/Filling ability	Slump Flow	SF3	760-850 mm
Viscosity/Flowability	T500	VS1/VF1	2.5 Secs
	V Funnel	VS1/VF2	10 Secs
Passing ability	L- Box	PA1	85%
Segregation resistance	sieve segregation	SR2	<20%

Mix Proportions and Performance

Concrete mix proportions approved after extensive laboratory and field trials using varied combinations of admixtures successfully for SCC mixes are demonstrated in Table 2 for reference. Long term strength gain of these mixes was also tested for upto a period of one year.

Table 2 Monorail SCC mix proportions and results

GRADE	TOTAL BINDER	% FLY ASH	w/b RATIO	7 DAYS	28 DAYS	365 DAYS	90 DAYS RCPT
M-45SCC	535	27	0.33	34.21	52.16	70.87	870.5
M-60SCC	620	27	0.29	44.34	63.24	87.02	-

Production control of SCC mix was identified as an important factor, so a comprehensive quality control plan helped in producing consistent quality of SCC with an excellent standard deviation of 3.9. The statistical analysis using moving averages is displayed in Figure 2.

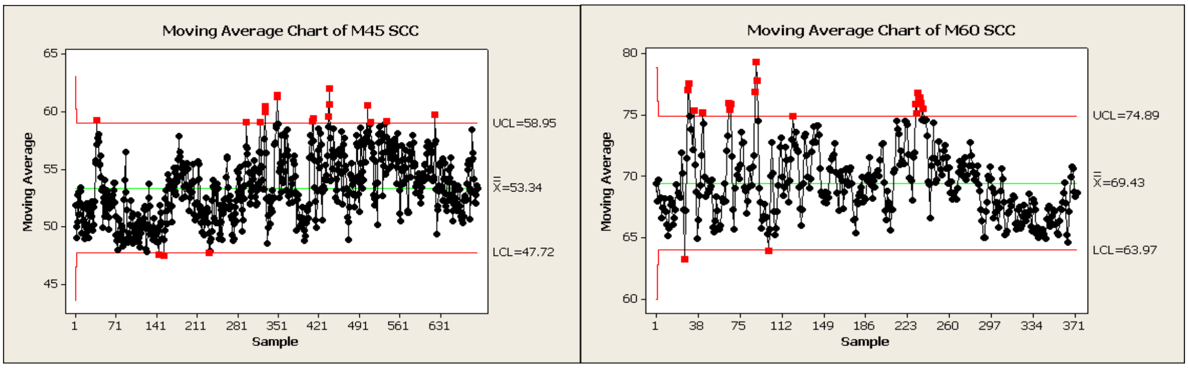

Figure 2 Statistical analysis of monorail M45 and M60 results.

DURABILITY ENHANCED CONCRETE FOR COMMERCIAL CONVENTION CENTRE

Project Requirements

Considering high level of deterioration due to environmental aggression in many high prestige commercial complexes, there has been increasing trend of durability based specifications for such structures in Mumbai, especially in the areas which have close proximity to Mithi River and the Arabian Sea. The reason for such history of damage has been concrete being exposed to higher concentration of chlorides and sulphates. This has had detrimental effect on serviceable life of structures. The unique feature of this iconic project is use of medium grade of concrete with stringent durability specification based on severity of exposure.

Design Stipulations

Typical elements of this building located very close to the Mumbai airport are specified with characteristic compressive strengths of 30 to 50 MPa. However, most of the 30,000 cubic metre concrete being used in this structure is specified with maximum allowable RCPT values of 800, 1000 and 3000 coulombs based on category of exposure. The expected durability monitoring frequency is similar to cube testing itself. The durability specifications for the commercial complex project are displayed in Table 3.

Table 3 Durability Specifications for Commercial complex

Test	Blinding and plain cement concrete	Moderate internal superstructure RC and post tensioned slabs/beams/columns/walls	Severe external superstructure RC and post tensioned slabs/beams/columns/walls	Very severe external substructure piles/pile caps (in contact with the ground)	Very severe external superstructure columns/walls/slabs (in contact with the ground)	Very severe external water retaining structures
Rapid Chloride Permeability (RCPT)to AASHTO T277 Max charge pass (coulombs) at 28 days	N/A	<3000	<1200	<1000	<1000	<800
Water Permeability (DIN) to DIN 1048 max penetration (mm) at 28days	N/A	<15	<10	<10	<10	<8
Initial surface absorption test (ISAT) to BS 1881 Part 208: maximum ISAT at 28 days : 10 minute test (ml/m2/s)	N/A	<0.3	<0.15	<0.15	<0.15	<0.02
30 minute absorption (WA) to BS 1881 part 122: 30 minute test (at 28 days unless noted otherwise)	2%Max	Max 1.5%	Max 1.5%	Max 1.5%	Max 1.5%	Max 1.5%

Material Selection and Design Approach

Concrete mix proportion approach involved meticulous selection of raw materials and study of individual raw material and their contribution to chloride and sulphide ion in the overall mix. Water to binder ratio was determined based on inter-proportion of cementitious material, optimum aggregate grading and water demand. Proper micro-fine binder proportioning leads to better particle packing resulting in lesser voids which leads to lesser water demand and high durability.

Mix Proportions and Performance

The mix proportioning of M40 grade high durability concrete resulted in a triple cementitious blend mix with a binder Content of 508 kg/m3 with water-binder ratio of 0.29. This mix could achieve average RCPT value of 551 coulombs. The water permeability was reported 12.5mm against a stringent maximum specified value of 15mm. Initial surface absorption test (ISAT) reported a value of 0.02 ml/m2/s as per DIN standard.

Mix Ingredients adopted were a triple blend using microsilica (5%) and flyash (30%), with a total binder content 508 kg/m3 and water binder ratio of 0.3 for M40 mix with maximum RCPT of 800 coulombs. Figure 3 demonstrates the statistical performance of the concrete used.

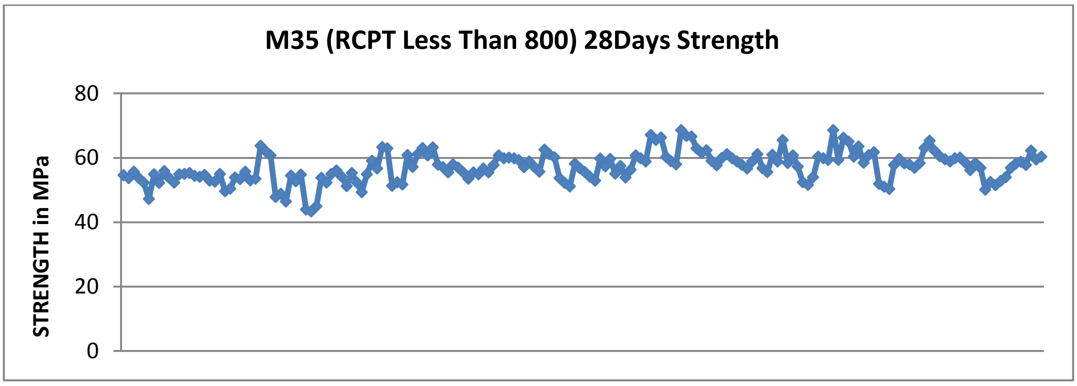

Figure 3 Statistical analysis of high durability M35 grade concrete.

HIGH STRENGTH DURABLE CONCRETE FOR A HIGH RISE TOWER

Project Requirements

In high rise buildings, rafts and shear walls are designed with very high strength concrete as mass concrete structure. Concrete generates heat as the cementitious materials hydrate and unlike thin sections; in this case, temperature rises to extremely high levels. Therefore management of concrete temperatures is necessary to prevent thermal cracking and to ensure compliance to strength requirement in the member. This project involved a 72-storey residential building of height 325 meters. The project required minimization of concrete core temperature and differential temperature of high performance M80 grade of concrete. Moreover, the durability specifications were to be complied and pumpability of concrete was to be ensured at challenging levels beyond 200 meters.

Design Stipulations

Grade of concrete :	M40 – Raft Concrete and M80 – Shear Column (at 90 days)
Slump Flow :	SF1 class - not less than 550 mm

Pumpability : Height of pumping up to 150 m for M80
Maximum core temperature : 75 °C
Maximum temperature differential: 20 °C
Maximum placing temperature : 28 °C
Additionally, all mechanical properties like E-Value, drying shrinkage, creep, cylinder compressive strength were to comply with the requirements of ASTM C 94.

Material Selection and Design Approach

A variety of mineral admixtures (normal as well as ultra-fine) were studied (Figure 4) and an optimum combination was used for improving the workability and reducing the core temperature of concrete. Standard consistency and rheology tests were carried out on various concrete mixes to select the combination of mineral admixtures. A quadruple blend was found to improve the concrete workability despite low water content with low core temperature for this high strength concrete. It was observed that standard consistency (Table 4) of cement paste with this quadruple blend is considerably lower as compared to other combinations. This combination of ordinary portland cement (OPC), ground granulated blastfurnace slag (GGBS), ultrafine slag and fly ash also demonstrated best results in terms of lowering the yield stress and viscosity to enable high-rise pumping. Appropriate selection of PCE based superplasticiers alongwith viscosity modifiers was made to derive consistent mix performance with respect to fresh properties.

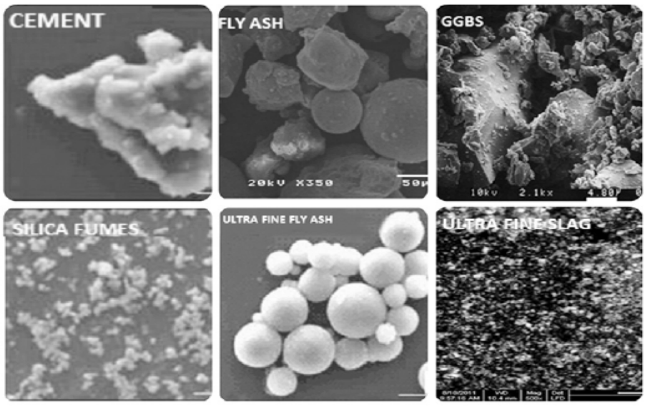

Figure 4 Scanning electronic microscopic image of cement, fly ash, ultrafine slag, ultrafine fly ash and silica fume.

Table 4 Standard consistency for various binder combinations

Trial no.	Cement	Fly ash	GGBS	Ultra fine slag	Silica fume	Ultra fine fly ash	Standard consistency
1	710.00	-	-	-	-	-	32.5
2	475.00	165.00	-	-	-	-	32
3	475.00	120.00	0.00	0.00	60.00	0.00	33
4	335.00	-	335.00	-	-	-	31.5
5	315.00	0.00	280.00	0.00	0.00	50.00	31
6	300.00	0.00	320.00	45.00	0.00	0.00	31
7	300.00	65.00	240.00	45.00	0.00	0.00	30

Mix Proportions and Performance

In order to take full advantage of secondary hydration of mineral additives, characteristic compressive strength of shear columns of M80 grade was targeted for 90 days. Additional performance criteria like E-value, drying shrinkage and creep were also determined. E-value of 45GPa and drying shrinkage of 0.0062% were reported for this mix.

TEMPERATURE CONTROLLED CONCRETE FOR RAFT OF A HIGH RISE TOWER

Project Requirements

This prestigious high rise residential building project in Mumbai characterized a unique combination of HPC requirements. The grades of concrete specified range from M40 to M70. The M60 grade raft has been designed with thickness ranging from 2 to 3 metres at various locations, thus applying mass concrete requirements of peak temperature and temperature differential. The concrete needed to be tested for cylinder strengths as per ASTM requirements. All durability and other mechanical properties need to be monitored.

Design Stipulations

Grade of concrete :	M60 (56 days)
Maximum core temperature :	75 °C (mockup size 2m x 2m)
Maximum temperature differential:	20 °C
Maximum placing temperature :	28 °C

Material Selection and Design Approach

A quadruple blend mix with high cement replacement level was adopted to ensure slow rate of initial hydration. The selection of superplasticisers was such as to produce concrete with suitable workability and viscosity. Placing temperature of concrete was reduced below 25 degree Celsius. Repeated mockup tests were conducted to monitor temperature rise to arrive at suitable mix. Mixes were also designed for SCC properties to ensure speedy casting.

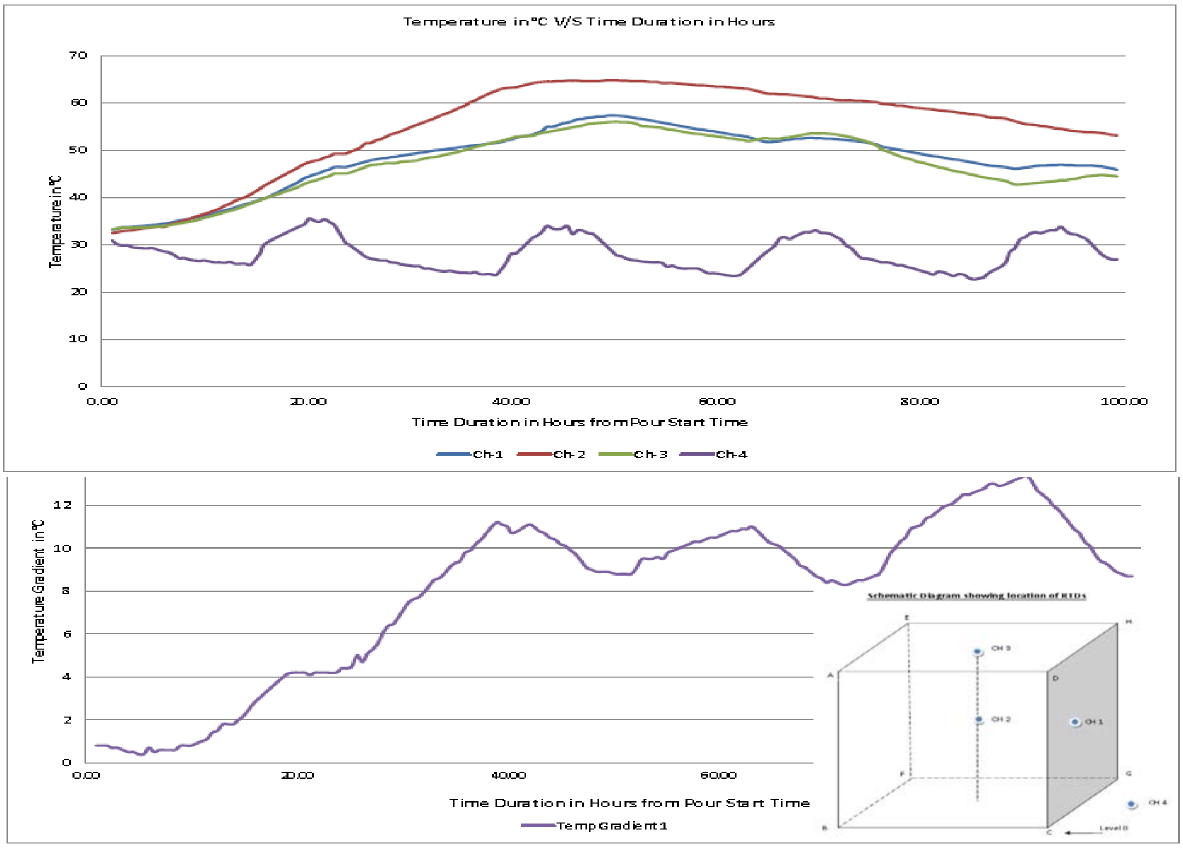

Figure 5 Peak temperature monitoring of mass concrete raft mockup

Mix Proportions and Performance

The final mix proportion for M60 grade temperature monitored SCC raft was designed with 650 kg per cubic metre total binder content with water binder ratio 023. OPC content in the mix was kept at barely 195 kg per cubic metre, while flyash, GGBS and ultrafine slag were kept at 36%, 31% and 4% respectively. Because of the large size of concrete pour, the concrete was supplied from four different plants, keeping the raw material sources fixed. The temperature of fresh concrete was closely measured and monitored. The temperature of ingredients of concrete was reduced to as low as possible. The 7, 28 and 56 days compressive strength results achieved were 38, 63 and 71 MPa respectively. Figure 5 displays the mockup results of the peak temperature and temperature differential using this mix.

LIGHTWEIGHT INSULATING CONCRETE FOR BUILDING ROOFS

Project Requirements

The two case studies considered for this sustainable product pertain to residential and industrial roof elements. In first case, traditional brickbat coba was replaced by lightweight concrete in order to attain overall energy savings. 100mm thick insulating layer was placed at flowable workability at the floor height of 6 meters for a residential house at Patiala. The purpose was thermal insulation. In the second case, an Industrial building in Noida (Figure 5), 100mm thick lightweight concrete was required to be spread on roof at a height of 12 meters, for the purpose of roof insulation.

Fig. 6 Placement of lightweight concrete for roof insulation

Design Approach and Performance

A combination EPS beads based mortar and foam concrete was utilised to design the mixture to attain the specified fresh densities. Overall composition of the concrete mixture comprised of OPC, flyash, sand, water, polysterene beads and foam. The density of 800 and 1100 kg/cum was achieved respectively. Placement of concrete was done after transportation time ranging from 45 to 90 minutes at a pumpable and flowable workability. The placement process involved manually spreading of concrete without any requirement of compaction. The concrete hardening time was 24 hours. 28 days strength was in the range 2-3 MPa. The reported thermal conductivity values were ranging from 23-27 W/mK.

IMPACT ON DURABILITY, SERVICE LIFE & SUSTAINABILITY

Durability, and sustainability based mixture proportioning requires selection of a proper combination of supplementary binders and their adequate replacement levels. Expert literatures provide specific models for arriving at proper choices. Water content needs to be kept optimum. Water binder ratio is to be as low as possible. OPC content should be kept as low as possible subject to early strength requirements. Fourth generation PCE based superplasticisers, retarders, VMA and additives like fibers help in modifying green and hardening characteristics of HPC.

Self compacting concrete helps in reduction in porosity and surface defects in the concrete structures. A dense and defect-free microstructure improves the structures resistance to environmental attack and significantly enhances the life of the structures compared to typical construction. It also helps in reducing the overall project duration. Elimination of usage of vibrators in sites reduces noise pollution, especially in the context of urban construction.

Durability enhanced concrete is much more resistant to environmental exposure and reduces subsequent maintenance and rehabilitation requirements. It also incorporates the usage of supplementary cementitious materials, which are often by-products and save natural resources.

High strength high performance concrete enables the designers to enhance the space utilisation by reducing the column dimensions. This also incorporates the usage of supplementary cementitious materials, thereby offering sustainable alternatives to construction methods. Often high strength concrete provides additional properties like early formwork removal, better placeability and higher durability.

Temperature controlled concrete helps in reduction of internal cracking in mass structures like raft foundations, core walls and mega columns. This positively impacts the life of structures. In order to restrict peak temperature rise within large rafts, often the concrete technologists and designers are forced to use alternative specifications and materials which are much more sustainable compared to traditional materials.

Lightweight concrete is normally a low strength non-structural concrete that has inherent thermal insulation property. Apart from that it exhibits high fire resistance and sound absorbent characteristics. These properties lead to tremendous energy saving, safety and functional superiority at marginal incremental costs. The structural version of lightweight concrete is also a possible alternative in order to achieve sustainable and energy efficient buildings.

CONCLUDING REMARKS

The various concrete varieties used in the case studies described in this paper prove the scalability of laboratory work done in the area of design of special varieties of concrete. With usage of modern alternative materials, cost effective, durable and sustainable types of concrete like self compacting concrete, durability enhanced concrete, high strength concrete, temperature-controlled concrete and lightweight concrete can be specified in construction work. The results reported in these cases matched the design specifications and provided the performance required.

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